Development of the Aqua MODIS NDSI Fractional Snow Cover Algorithm and Validation Results

V. V. Salomonson, Fellow, IEEE, and Igor Appel

Abstract—The principal purpose of this paper is to describe the development and validation of an algorithm to estimate the fraction of snow cover within a 500-m pixel of the Moderate Resolution Imaging Spectroradiometer (MODIS) operating on the Earth Observing System Aqua spacecraft. The performance of this algorithm and algorithms applicable to the MODIS on the Terra spacecraft are compared. Validation efforts show that both pixel-level, fractional snow cover relationships for the Terra and Aqua MODIS instruments work well as quantified by such measures as correlation coefficient (r) and root-mean-square error when compared to Landat-7 Enhanced Thematic Mapper ground-truth observations covering a substantial range of snow cover conditions. Over all the scenes used herein, the correlation coefficients were near 0.9 and the RMSE near 0.10. However, somewhat better performance was found for the Terra MODIS versus the Aqua MODIS over nearly concurrently observed scenes. Furthermore, it is clear that more improvements in fractional snow cover estimates within MODIS pixels should be pursued to better account for variability in slope and aspect, atmospheric effects, snow cover types, and land cover.

Index Terms—Aqua mission, Earth Observing System (EOS), fractional snow cover, ground truth, Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS), pixel, snow cover, Terra mission.

I. INTRODUCTION AND BACKGROUND

In A RECENT paper by Salomonson and Appel [1], a method, accompanying rationale, and results were described wherein the normalized difference snow index (NDSI) was used to provide an estimate of the snow fraction within each pixel of the Moderate Resolution Imaging Spectroradiometer (MODIS) operating on the NASA Earth Observing System (EOS) Terra spacecraft. The purpose of that paper was to extend the present MODIS approach for mapping snow called "SNOWMAP" [2]–[4] wherein each MODIS 500-m pixel is classified as snow or nonsnow. The paper showed that a fairly robust determination of the fraction of snow cover within 500-m MODIS pixels (FRA) was obtained and the associated algorithm could be employed in the daily, global processing of MODIS data with existing computational resources.

The overall characteristics of the MODIS instrument that operates on both the EOS Terra and Aqua missions are provided by Barnes *et al.* [5]. Essentially, the MODIS instrument provides daily, global coverage in 36 spectral bands extending from visible through thermal infrared wavelengths at spatial resolutions

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The authors are with the Earth–Sun Division, NASA, Goddard Space Flight Center, Greenbelt, MD 20715 USA.

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ranging from 250 m to 1 km. The Terra spacecraft orbit goes from north to south on the daylight side of the Earth nominally crossing the equator at 10:30 A.M. local time. The Aqua MODIS spacecraft orbit goes from south to north on the daylight side of the Earth crossing the equator at 1:30 P.M. In this paper, only the relevant MODIS bands having 500-m spatial resolution are

In the SNOWMAP and fractional snow cover approach [1]–[4], the NDSI, along with a series of threshold tests and the MODIS cloud mask [6], is employed. The NDSI is a spectral band ratio that takes advantage of the fact that snow reflectance is high in the visible wavelengths (0.4–0.7 μ m) and low in the shortwave infrared region (1–4 μ m). This ratio has proven to be quite useful in separating snow from clouds as well as from nonsnow-covered surfaces. The NDSI is defined as the difference of reflectances observed in a visible band such as the MODIS band 4 (center wavelength is at 0.555 μ m) and a shortwave infrared band such as MODIS band 6 (1.640 μ m) divided by the sum of those reflectances. For the purposes of this paper this ratio will be called "NDSI6"

$$NDSI6 = (b4 - b6)/(b4 + b6).$$
 (1)

Equation (1) was only applied to data from the MODIS instrument on the Terra satellite.

The motivation for this paper comes from the fact that the Aqua MODIS instrument band 6, nominally centered at 1.640 μ m, has 15 out of 20 of the accompanying detectors that are nonfunctional. Therefore, (1) cannot be employed using Aqua MODIS observations. Because in many circumstances over land surfaces there is a fairly high correlation between the reflectances of MODIS band 6 and band 7 centered at 2.130 μ m, it was decided to see if (1) could use band 7 values in place of band 6 and still achieve useful estimates of fractional snow cover (FRA) in 500 m pixels. The same basic physics relative to separating snow from clouds and other surfaces applies, but the magnitude of the reflectances acquired in that band is markedly lower than in the 1.640- μ m region and, subsequently, the band ratio effective "signal to noise" may be problematic. The new NDSI (hereafter designated NDSI7) can be expressed as

NDSI7 =
$$(b4 - b7)/(b4 + b7)$$
. (2)

The principal purpose of this paper, therefore, is to describe the development and validation of the algorithm using NDSI7 for mapping fractional snow cover using Aqua MODIS observations. In the course of doing this, the paper will describe comparative

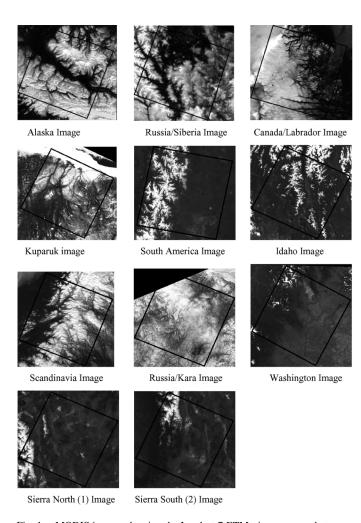


Fig. 1. MODIS images showing the Landsat-7 ETM+ image areas that were used to develop MODIS Fractional Snow Cover (FRA) versus MODIS (NDSI) relationships and validate results.

results using Terra MODIS observations where both bands are operative. Comparisons of fractional snow cover estimates by both Aqua MODIS using NDSI7 and Terra MODIS using NDSI6 will also be made over selected areas on a given day utilizing nearly concurrent Landsat-7 Enhanced Thematic Mapper (ETM+) observations for comparisons and validation of the results.

II. APPROACH

Given that both Band 6 and Band 7 work well on the Terra MODIS instrument, the first step was to develop a regression relationship ("FRA7") between fractional snow cover within a 500-m MODIS pixel and NDSI7 (2) for Terra and compare it to results (i.e., "FRA6") using (1). The same Landsat scenes used in [1] over Alaska, Labrador, and Russia were employed to develop the regression relationships for FRA7. The nominal location, date, etc., for these Landsat scenes, and other Landsat scenes used in this investigation, are given in Table I. MODIS images, including the areas covered by the Landsat scenes, are shown in Fig. 1.

In essence, the procedures used to establish the fraction of snow in a MODIS pixel and relate it to the NDSI were the same as that described in [1]. In summary, nearly concurrent,

same-day, Landsat scenes and MODIS scenes, as depicted in Fig. 1, were registered to a 500-m grid. Within each grid cell the 30-m Landsat ETM pixels were classified as snow-covered or not using the "SNOWMAP" approach [4]. For each 500-m grid cell, the percentage of snow cover was determined on the basis of Landsat observations by counting the number of Landsat ETM+ pixels covered by snow versus the total number of Landsat pixels in the cell. For each grid cell, top-of-the-atmosphere reflectances from MODIS observations were determined using bilinear interpolation between centers of MODIS pixels and the NDSI computed using (1) or (2). The percentage of snow cover determined from Landsat ETM+ in each cell was then compared to the MODIS NDSI estimates. Scatter plots showing fractional snow cover versus NDSI were studied and regression relationships both for fractional snow cover (independent variable) with NDSI and NDSI (independent variable) with fractional snow cover computed. The best results came from regressing fractional snow cover (independent variable) versus NDSI. This approach was used because the fractional snow cover (FRA) derived from Landsat observations is better determined than the MODIS NDSI and secondly, when doing an ordinary least squares analysis (OLS) of NDSI on FRA, the analysis minimizes the variance of NDSI over a range of FRA between 0.0 and 1.0. Doing the FRA on NDSI minimizes the FRA variance for values of FRA greater than 1.0 and less than 0.0 and these conditions do not occur. Because the objective is to obtain fractional snow cover from NDSI, the NDSI on FRA relationship was inverted algebraically so as to obtain fractional snow cover estimates from NDSI. The basis, justification, and rationale for this procedure are described in more detail in [1, p. 354]. Using the results derived from three scenes, an average relationship was computed with the intent and purpose of using this relationship for obtaining fractional snow cover estimates over the land areas of the globe. This averaged relationship was then applied to independent sample regions to validate the effectiveness of this result.

In the course of developing the regression relationship between fractional snow cover and NDSI using band 7, the existing relationship derived in [1] using band 6 from MODIS Terra was reexamined. Previously the regression relationship was developed for conditions where the true fraction of snow in 500-m cells was >10% (0.1) up to and including 100% (1.0) snow cover. Based on the study completed in [1], this produced the best performing algorithm. Further examination has resulted in concern about the effect of the high number of points clustered around 100% snow cover on the performance of the algorithm. Subsequently, a new criteria wherein conditions where snow cover was >0.1 and <0.95 was examined and, as will be discussed later, found to be preferable. It should be noted and as done previously in [1], once the FRA versus NDSI relationship was developed, it was used to estimate the fraction of snow in a 500-m pixel over the entire range from zero to 100% snow cover.

Using the approach described above, fractional snow cover estimates {i.e., FRA6T = f(NDSI6) and FRA7T = f(NDSI7)} based on Terra MODIS observations were then compared and tested using areas over the Kuparuk River watershed in Alaska and in the Andes in South America. As in

TABLE I
INFORMATION ABOUT LANDSAT-7 ETM+ SCENES USED AS GROUND TRUTH IN DEVELOPING AND TESTING STATISTICAL
RELATIONSHIPSBETWEEN FRACTIONAL SNOW COVER (FRA) AND THE NORMALIZED DIFFERENCE SNOW INDEX (NDSI).
FRA6 IS BASED ON MODIS BANDS 4 AND 6. FRA7 IS BASED ON MODIS BANDS 4 AND 7

Region	Day	Path	Row	Sun	Sun	Gain Settings	Projection
٥				elevation	azimuth	for Landsat	
				(degrees)	(degrees)	bands 2,5,7	
Landsat scenes					d FRA7		
estimates deriv							
Alaska	05/12/01	065	17	46	162	LHH	UTM
Russia/Siberia	05/24/01	142	13	43	168	HHH	UTM
Labrador	11/07/00	011	20	15	168	ННН	UTM
Landsat scenes MODIS observ		t FRA6	estimate	es derived fro	om Terra		
Kuparuk	05/23/02	073	11	41	172	ннн	UTM
South America	12/08/01	232	84	58	077	LLL	UTM
Landsat scenes	used to dev	velop F	RA7 esti	mates derive	d from		
Aqua MODIS							
Washington	07/22/02	045	27	57	138	ННН	Albers Equal Area
Scandinavia	04/20/03	198	15	37	165	ННН	UTM
Russia/Kara	05/20/03	168	12	42	170	ННН	UTM
Landsat scenes MODIS observ		t FRA7	estimate	es derived fro	m Aqua		
Idaho	05/24/03	043	26	58	144	ННН	Albers Equal Area
Sierra North (1)	04/08/03	041	34	53	138	ННН	Albers Equal Area
Sierra South (2)	04/08/03	041	35	54	136	ННН	Albers Equal Area
Landsat scenes							
estimates deriv				l FRA7 estin	ates		
derived from A			T	,			
Idaho	05/24/03	043	26	58	144	ННН	Albers Equal Area
Sierra North (1)	04/08/03	041	34	53	138	ННН	Albers Equal Area
Sierra South (2)	04/08/03	041	35	54	136	ННН	Albers Equal Area

[1], concurrent Landsat scenes were used as the "ground truth" for validation. For clarity, note in the FRA and NDSI labels that a "T" is used to denote application or use of Terra MODIS observations (later, an "A" will be used to denote use of Aqua MODIS observations) and the "6" or "7" denotes the band applied.

A next step was to evaluate pixel fractional snow cover estimates from Aqua MODIS observations. Given the similarity of the MODIS instruments on the Terra and Aqua missions, it was hypothesized that the FRA7T might work successfully when applied to Aqua MODIS observations and there not be a need to develop a FRA7A relationship. To confirm this hypothesis, however, regression relationships between pixel snow fraction and NDSI7 using Aqua ("A") MODIS observations were examined using the same approach as described when using Terra observations indicated above and a FRA7A = f(NDSI7) obtained. Three new areas with coincident Landsat-7 ETM+ scenes were selected to do this over Washington state, the Kara region of Russia, and a region in Scandinavia. These regions are depicted in Fig. 1 and the related Landsat scene information is given in Table I.

From the procedures described in the preceding paragraph, estimates of pixel fractional snow cover using the average FRA7T equation and an average FRA7A algorithm were derived. Both of these were tested (i.e., "independent test") on three scenes: a scene in Idaho and two scenes of the southern Sierra Nevada region of California. Again, the general snow cover characteristics for these three areas are shown in Fig. 1

and the accompanying Landsat ETM+ scene characteristics are described in Table I.

The last major step in this testing and validation effort was to compare nearly concurrent pixel fractional snow cover estimates from the Terra and Aqua MODIS observations over the same area and same day. To do this, the average FRA6T algorithm was applied to the Terra MODIS observations and the average FRA7A algorithm was applied to Aqua MODIS observations. The ground truth was derived from concurrent Landsat ETM+ observations. The principal assumption at this stage in the comparisons was that snow cover variations over the range of satellite overpass times associated with Aqua, Terra, and Landsat would be insignificant in that these observations are nominally separated in time by no more than about 3 h (i.e., difference in equator-crossing times).

III. RESULTS AND DISCUSSION

Fig. 2 shows the scatter plots comparing fractional snow cover in each 500-m grid cell determined from Landsat and the accompanying NDSI determined from Terra MODIS reflectances [see (1) and (2)]. The specific regression relationships achieved are listed in Table II. Table II also shows the averaged relationships for each of the above. In Fig. 2, the scatter around the regression line in each of the scenes tested (Alaska, Labrador, and Siberia) appear about the same with a little more scatter in the Siberia scene. This trend is borne out in Table II, showing that the root-mean-square error (RMSE) values are

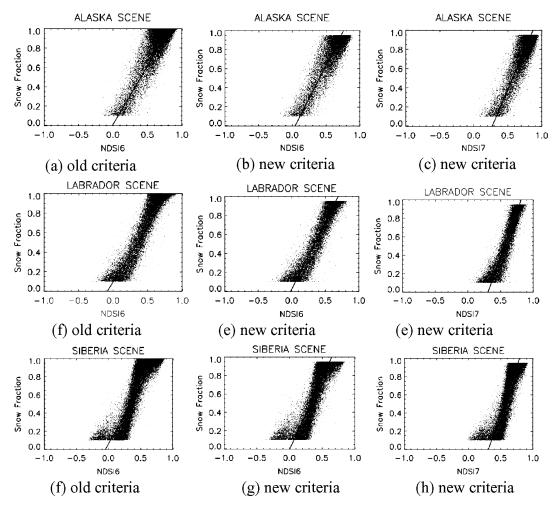


Fig. 2. Scatter plots showing the actual snow fraction based on Landsat ETM observations in 500-m grid cells versus the NDSI using Terra MODIS band 6 and band 7 observations. The "old" criteria used observations in the cells where the snow fraction was above 0.1. The "new" criteria used observations in the cells where the snow fraction was between 0.1 and 0.95.

a little higher in the Siberia scene than in the Labrador and Alaska scenes. The reasons are probably due to more variability in snow type and none snow-covered conditions. In addition, it should be noted that the correlation coefficients are lower when the 0.1–0.95 criterion is used, but the RMSE is smaller/improved. This is due to not having the extra pixels with above 0.95 snow cover to use in the correlation. The difference in the number of pixels in the correlation is shown in the last column of Table II. It should also be noted that in terms of correlation coefficient and RMSE the FRA6T and the FRA7T results using the new 0.1–0.95 criteria are very similar.

The averaged ("universal") relationships for each of FRA6T (old), FRA6T (new), and FRA7T were tested on the scenes over the Kuparuk River watershed in Alaska and a region in the Andes of South America by using concurrent Landsat data as ground truth. The comparison of snow fraction calculated on the basis of MODIS FRA relationships with the Landsat ground-truth is shown in Fig. 3 (solid line) versus a 1-to-1 line (dashed line). Comparative results showing the values of the correlation coefficient (r) and RMSE are shown in Table III. The results for both the Kuparuk and South American scenes shown in Table III are rather similar although the correlation coefficient (r) is little better and the RMSE is

also somewhat better (smaller) for the South America scene than for the Kuparuk scene. The visual appearance of the scatter in Fig. 3 on the other hand appears a little larger for the South American scene than the Kuparuk scene. It is believed that these differences can be attributed to a greater proportion of zero snow cover values (hence, the calculated and ground truth values agree) due to the mean snow cover being smaller than in the Kuparuk case snow cover (i.e., both the calculated and ground truth agree at zero values). The large number of zero values tends to keep the regression line running close to or through zero, raises the correlation coefficient, and counter-balances scatter around larger values of fractional snow cover resulting in a lower RMSE as compared to the Kuparuk scene. It is believed that variability of terrain and accompanying shadowing, variability in land cover (i.e., vegetation, bare soil, or rock in pixels without snow), and atmospheric variability contributes to the scatter in the plots for both regions.

Based on Table III and Fig. 3, there appears to be no major advantage for FRA6T (new) versus FRA6T (old) although the virtue of FRA6T(new) is that it relies less on the heavy concentration of points at or very near 100% and subsequently is judged to be more robust in general than the FRA6T (old) relationship.

 ${\it TABLE~II} \\ {\it Regression~Relationships~Developed~for~Snow~Fraction~Using~Terra~MODIS~Observations} \\$

Regions (mean snow cover fraction)	Algorithm	Version	Regressions with NDSI	Correlation Coefficient (r)	Root- Mean- Squared -Error (RMSE)	Number of Pixels
Alaska	FRA6T	OLD	0.01+1.21*NDSI6	0.89	0.087	106,860
(78%)		NEW	-0.06+1.39*NDSI6	0.83	0.084	23,609
	FRA7T		-0.45+1.66NDSI7	0.84	0.082	23,609
Labrador	FRA6T	OLD	0.10+1.13*NDSI6	0.92	0.101	72,248
(67%)		NEW	0.03+1.41*NDSI6	0.86	0.094	25,668
	FRA7T		-0.61+1.97*NDSI7	0.85	0.097	25,668
Siberia (40%)	FRA6T	OLD	0.06+1.28*NDSI6	0.90	0.115	95,618
		NEW	0.00+1.56*NDSI6	0.82	0.105	32,535
	FRA7T		-0.63+2.06*NDSI7	0.80	0.109	32,535
	FRA6T	OLD	0.06+1.21*NDSI6			
Average ("universal")		NEW	-0.01+1.45*NDSI6			
relationship	FRA7T		-0.56+1.90*NDSI7			
0.8 0.8 0.6 0.4 0.4 0.2 0.0 0.0 0.2	PARUK SCENE 0.4 0.6 0.8 Ground Truth	0.0 Colonidate Procession 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.		0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0	KUPARUK SC 0.2 0.4 0.6 Ground Trut	0.8 1.0
FRA6 -	- OLD - UNIVERS AMERICA SCEN		FRA6 - NEW - UNIVERSA SOUTH AMERICA SCE		FRA7 – TERF	RA .
1.0 Sootil		0.1 8.0 uaction		1.0 8.0 eti		

Fig. 3. Calculated snow fraction versus "ground truth" observations from Landsat-7 ETM+ scenes over the Kuparuk River in Alaska and the southern Andes in South America (see Table I).

0.4

Ground Truth

FRA6 - NEW - UNIVERSAL

0.6 0.8

It could be argued that either relationship could be probably used just as well, but because of the previous reasoning, the criteria (fractional ground truth within the range between 0.1 and 0.95) was employed throughout this paper not only for es-

0.4 0.6 0.8 1.0

Ground Truth

FRA6 - OLD - UNIVERSAL

0.2

0.4

0.0

tablishing the FRA6T(new) algorithm but also in establishing FRA7 relationships. It was encouraging to see the FRA7T relationship performing nearly or just as well as the FRA6T relationships given that the "signal to noise" (i.e., the smaller range

Ground Truth

Calculated

1.0

0.4

0.0

0.2 0.4 0.6 0.8 1.0

TABLE III
RESULTS DERIVED WHEN TESTING REGRESSION RELATIONSHIPS OF FRA VERSUS NDSI FOR INDEPENDENT SCENES OVER THE KUPARUK RIVER IN ALASKA AND THE SOUTHERN ANDES IN SOUTH AMERICA (SEE TABLE I FOR LANDSAT SCENE DETAILS) USING TERRA MODIS OBSERVATIONS

Total Number of pixels (Number of pixels with snow) Mean snow cover %	Region	Model	Version of model	Correlation Coefficient (r)	Root Mean Square Root Error (RMSE)	Regression of calculated fraction with ground truth
120,137	Kuparuk	FRA6T(old)	Universal For Terra	0.90	0.12	-0.01+1.00*T
(108,809)		FRA6T(new)		0.89	0.13	-0.02+1.05*T
41%		FRA7T		0.87	0.15	-0.02+1.05*T
135,720	South America	FRA6T(old)	Universal For Terra	0.94	0.10	0.01+1.08*T
(48,750) 18%		FRA6T(new)		0.93	0.11	0.01+1.12*T
		FRA7T		0.91	0.10	-0.01+1.02*T

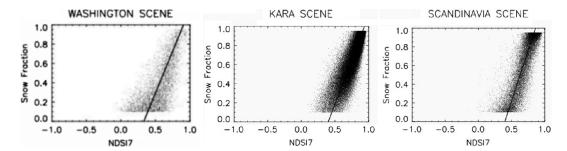


Fig. 4. Several regressions of snow fraction versus Normalized Difference Snow Index (NSDI7) based on Aqua MODIS observations, i.e., FRA7A versus NDSI7. As before, the NDSI observations were constrained to 0.1 and 0.95 in developing the regression relationships.

of reflectances observed in the band 7) notionally seemed to indicate it would not do as well. More discussion about FRA7 relationships follows. The FRA6T (new) relationship (3) is the one that is to be prepared for application to Terra MODIS data in future forward processing and reprocessing of all data from the start of MODIS data collection in February 2000 (termed "Collection 5"). The Collection 5 effort is projected to begin in the spring of 2006 and extend through most of 2007

$$FRA6T = -0.01 + 1.45*NDSI6.$$
 (3)

As was done in the procedure leading to Fig. 2 for all the dependent samples leading to FRA relationships for Terra MODIS data, Fig. 4 depicts "dependent sample" scatter plots for fractional snow cover versus NDSI (i.e., FRA7A versus NDSI7) using band 7 (2) and Aqua MODIS observations for scenes over a portion of Washington state, the Kara region of Russia, and a region in Scandinavia. Again, similar to Table II showing results using Terra MODIS observations, Table IV lists the particulars for the plots in Fig. 4 along with the regression relationships for each of the scenes and the average relationship (FRA7A) derived from the 3 scenes. As can be seen in Fig. 4 and Table IV, the results using Aqua MODIS data are similar to those using Terra MODIS data shown in Fig. 2 and Table II. However, the quality of the results from the Washington state scene is lower than any of the others. This is attributed to the Washington scene being

more heavily forested than other scenes used in this study, substantial terrain relief and shadowing, and much less snow with which to develop the regression relationship.

The average FRA7A, FRA7T relationships were tested on three scenes over Idaho, and the southern Sierra Nevada mountains in California. Again, concurrent Landsat ETM+ snow cover fraction for 500-m grid cells was used as the ground truth. The results are described in Fig. 5 and Table V. The results listed in Table V show that the correlation coefficients and RMSE values are comparable to those shown in Table III. However, as was discussed above relative to Table III and Fig. 3 for the South American scene, each of the scenes used in Fig. 5 and Table V have lower mean snow cover amounts resulting in a large fraction of all the pixels observed being calculated as zero values and also, as a result, larger deviation from the 1-to1 line at higher fractional snow cover values. In addition all the scenes have substantial terrain variability and forested areas leading to greater scatter around the regressions lines in Fig. 5.

In general, the fractional snow cover results when tested on independent scenes indicate that neither FRA7T (FRA7T = -0.56 + 1.90 NDSI7) nor FRA7A (FRA7A = -0.72 + 1.91NDSI7) consistently performs better than the other. Therefore, a further averaging of these two relationships was also tested. Ultimately, it was judged that this combined relationship (designated FRA7U) would be the pragmatic

TABLE IV
REGRESSION RELATIONSHIPS DEVELOPED FOR SNOW FRACTION USING AQUA MODIS OBSERVATIONS

Regions	Mean Snow Cover	Algorithm	Regressions with NDSI	Correlation Coefficient (r)	Root- Mean- Squared -Error (RMSE)	Number of Pixels
Russia- Kara	77%	FRA7A	-0.74+1.85*NDSI7	0.86	0.102	79,809
Scandinavia	70%	FRA7A	-0.85+2.15*NDSI7	0.83	0.087	20,213
Washington State USA	2%	FRA7A	-0.57+1.73*NDSI7	0.70	0.178	3,728
Average Re	lationship	FRA7A	-0.72+1.91*NDSI7			

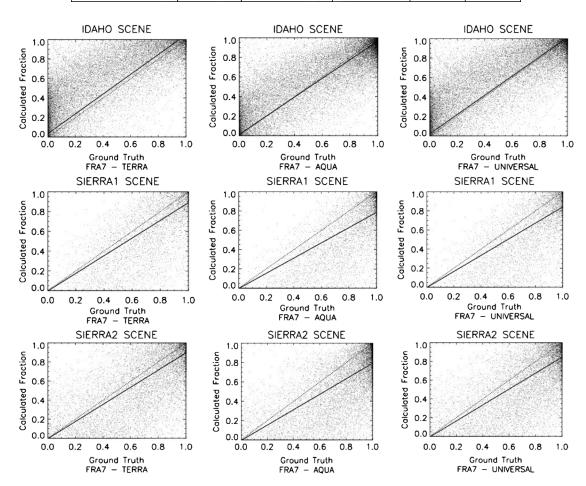


Fig. 5. Calculated snow fraction versus ground truth observations from Landsat-7 scenes over the Idaho and the southern Sierra Nevada mountains in the U.S. (see Table I for Landsat-7 ETM+ scene details).

selection for the final FRA7 algorithm to be applied to Aqua observations. The FRA7U relationship is

$$FRA7U = -0.64 + 1.91NDSI7.$$
 (4)

As indicated in Section II, the next step in validating fractional snow cover results was to compare fractional snow cover results obtained on the same day from the Terra and Aqua MODIS data versus concurrent Landsat observations. These results are shown in Fig. 6 and Table VI. As noted in Figs. 6 and 7 and

Table VI, the scene over Idaho and the two Sierra Nevada scenes were used. FRA6T (3) was applied to the Terra MODIS data and FRA7A (4) was used on the Aqua data. The results given in Table VI and depicted in Fig. 6 show that comparable performance was obtained. Visual comparison of the results shown in Fig. 7 also leaves this impression. Further examination of the results in Table VI indicates, however, that there is some advantage to the Terra MODIS FRA6T results. This most likely may be due to the fact that the band 7 on one of the cooled focal planes of the Aqua MODIS is more misregistered to band 4 on

Number of pixels (Number of pixels with snow) Mean snow cover	Region	Model	Version of model	Correlation Coefficient (r)	Root Mean Square Error (RMSE)	Regression of calculated fraction with ground truth
116,592	Idaho	FRA7T	Average for Terra	0.90	0.12	0.03+1.02*T
(35,557) 18%		FRA7A	Average for Aqua	0.93	0.09	0.01+0.95*T
		FRA7U	Overall Average	0.92	0.10	0.02+0.99*T
128,693	Sierra1	FRA7T	Average for Terra	0.90	0.06	0.00+0.89*T
(10,330) 5%		FRA7A	Average for Aqua	0.86	0.07	0.00+0.79*T
		FRA7U	Overall Average	0.88	0.07	0.00+0.84*T
128,257	Sierra2	FRA7T	Average for Terra	0.89	0.09	0.00+0.90*T
(20,106) 9%		FRA7A	Average for Aqua	0.86	0.10	-0.01+0.80*T
		FRA7U	Overall Average	0.88	0.09	-0.01+0.85*T

 $TABLE\ \ V$ Results Comparing Fractional Snow Cover Estimates Over Independent Sites Using Aqua MODIS Observations

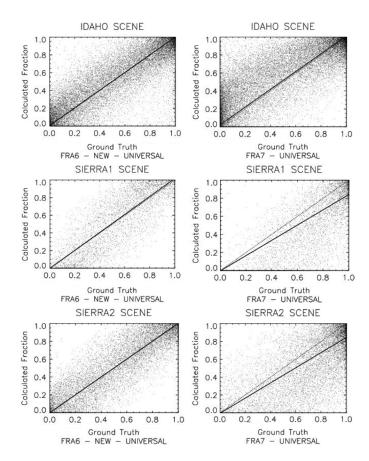


Fig. 6. FRA6T (3) was applied to same-day Terra MODIS data and FRA7U (4) was used on the Aqua data along with same-day Landsat-7 ETM+ scenes used as ground truth (see Table I for Landsat scene location details, etc.).

an uncooled focal plane. It was known before the launch of the Aqua MODIS that there was a misregistration of about 0.3 pixel versus 0.1 pixel on the Terra MODIS. However, to rectify this discrepancy was found to be too costly to warrant taking the actions to fix it prior to launch. Only recently have software proce-

dures been considered for the "collection 5" to reduce the effect of this misregistration not only with regards to snow cover mapping, but for other MODIS products.

IV. OVERALL CONCLUSION AND SUMMARY

This paper has developed and tested relationships for estimating fractional snow cover using data from the Terra and Aqua MODIS instruments. A relationship, FRA6T, employing the NDSI was refined and validated for use with Terra MODIS data and a similar relationship, FRA7U, was developed for application to Aqua MODIS data. Developing the FRA7 relationship was necessary because the band 6 (1.64 μ m) on the Aqua MODIS instrument is not useful because the majority of detectors are not functional. The resulting equations are

$$FRA6T = -0.01 + 1.45*NDSI6$$

 $FRA7U = -0.64 + 1.91*NDSI7$

These equations will be employed in the reprocessing of Terra and Aqua MODIS data for what is termed "Collection 5" and subsequently will be available to provide fractional snow cover estimates within MODIS pixels over the land areas of the earth. Validation efforts show that both pixel-level, fractional snow cover relationships provide useful results as measured in independent tests against fractional snow cover, ground truth obtained from Landat-7 ETM+ scenes covering a substantial range of snow cover conditions and quantified by measures as correlations coefficients and RMSE. Over all the scenes used herein to validate or test the relationship, the correlation coefficients were near 0.9 and ranged from 0.88 to 0.94. The corresponding RMSE values were near 0.1 and ranged from 0.07 to 0.15. (see Tables III and V). When tested on a scene where both instruments observed the same conditions at about the same time (separated by a nominal 3 h), the results were similar, but there could be seen some advantage to the Terra MODIS observations. It is felt this advantage of the Terra MODIS results over the Aqua

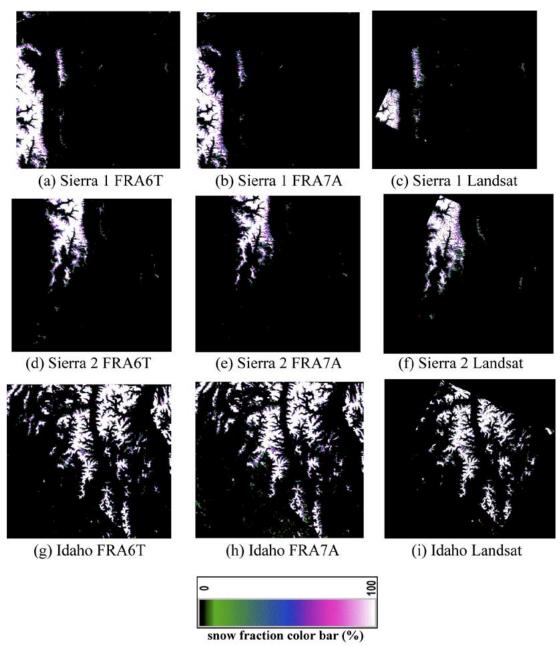


Fig. 7. Images (a), (d), and (g) are fractional snow cover estimates from Terra MODIS for 500-m cells using the FRA6T algorithm (3). Images (b), (e), and (h) are fractional snow cover estimates from Aqua MODIS for 500-m cells using the FRA7U algorithm (4). Images (c), (f), and (i) are images Landsat-7 ETM+ "ground truth" measures of snow fraction in 500-m grid cells.

TABLE VI
FRACTIONAL SNOW COVER ESTIMATES USING (3) APPLIED TO TERRA MODIS OBSERVATIONS AND FRACTIONAL SNOW COVER ESTIMATES
USING (4) APPLIED TO AQUA MODIS OBSERVATIONS COMPARED TO LANDSAT ETM+ GROUND TRUTH OBSERVATIONS

Number of pixels (Number of pixels with snow) Mean snow cover	Region	Model	Correlation Coefficient (r)	Root Mean Square Error (RMSE)	Regression of calculated fraction with ground truth	Satellite
N=116,592 (N=35,557)	Idaho	FRA6 T	0.96	0.07	0.01+1.00*T	Terra
18%		FRA7U	0.92	0.10	0.02+0.99*T	Aqua
N=128,693	a: 1	FRA6T	0.96	0.04	0.00+1.02*T	Terra
(N=10,350) 5%	Sierra1	FRA7U	0.88	0.07	0.00+0.84*T	Aqua
N=128,257		FRA6T	0.96	0.05	0.00+1.00*T	Terra
(N=20,106) 9%	Sierra2	FRA7U	0.88	0.09	-0.01+0.85*T	Aqua

MODIS is principally due to the 0.3 pixel misregistration of band 7 to band 4 (the two bands used in calculating the NDSI for the Aqua MODIS instrument) versus 0.1 pixel misregistration for band 6 to 4 in the case of the Terra MODIS instrument.

Even though the algorithms provided useful results in general, it is clear that improvements for specific areas are possible. Based on the approach described herein and using results from [1], Dery *et al.* [7] report an example where improved snow cover estimates over the Kuparuk watershed were achieved by suitably adjusting the snow cover algorithm for that specific area. In addition a spectral, end-member approach [8], [9] that explicitly takes into account land cover and snow characteristics in a specific region could be developed and applied with possibly better performance. Finally, and as mentioned in [1], correction for atmospheric effects, the bidirectional properties of snow, topography, etc., seem preferable ultimately. Research into these matters is continuing so as to improve the snow cover products from MODIS for local, regional, and global studies.

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REFERENCES

- V. V. Salomonson and I. Appel, "Estimating fractional snow cover from MODIS using the normalized difference snow index," *Remote Sens. Environ.*, vol. 89, pp. 351–360, 2004.
- [2] D. K. Hall, G. A. Riggs, and V. V. Salomonson, "Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data," *Remote Sens. Environ.*, vol. 34, pp. 127–140, 1995.
- [3] D. K. Hall, G. A. Riggs, V. V. Salomonson, N. E. DeGirolamo, and K. J. Bayr, "MODIS snow cover products," *Remote Sens. Environ.*, vol. 83, pp. 181–194, 2002.
- [4] A. G. Klein, D. K. Hall, and G. A. Riggs, "Improving snow-cover mapping in forests through the use of a canopy reflectance model," *Hydrol. Process.*, vol. 12, pp. 1723–1744, 1998.
- [5] W. L. Barnes, T. S. Pagano, and V. V. Salomonson, "Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS AM1," *IEEE Trans. Geosci. Remote Sens.*, vol. 36, no. 4, pp. 1088–1100, Jul. 1998.

- [6] S. Platnick, M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riedi, and R. A. Frey, "The MODIS cloud products: Algorithms and examples from Terra," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 2, pp. 459–473, Feb. 2003.
- [7] S. J. Dery, V. V. Salomonson, M. Steiglitz, D. K. Hall, and I. Appel, "An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modeling in Alaska," *Hydrol. Process.*, to be published.
- [8] T. H. Painter, J. Dozier, D. A. Roberts, R. E. Davis, and R. O. Green, "Retrieval of subpixel snow-covered area and grain size from imaging spectrometer data," *Remote Sens. Environ.*, vol. 85, pp. 64–77, 2003.
- [9] D. A. Roberts, M. Gardner, R. Church, S. Ustin, G. Scheer, and R. O. Green, "Mapping chaparell in the Santa Monica Mountains using multiple end member spectral mixture models," *Remote Sens. Environ.*, vol. 44, pp. 255–269, 1998.



Vincent V. Salomonson (F'98) received the B.S. degree in agricultural engineering from Colorado State University, Fort Collins, in 1959, the B.S. degree in meteorology from the University of Utah, Salt Lake City, in 1960, the M.S. degree in agricultural engineering from Cornell University, Ithaca, NY, in 1964, and the Ph.D. degree in atmospheric science from Colorado State University in 1968.

He is presently a Research Professor with joint appointments in the Departments of Meteorology and Geography, University of Utah, Salt Lake City,

and a Senior Scientist (Emeritus) in the Earth-Sun Division at the NASA Goddard Space Flight Center (GSFC), Greenbelt, MD. He is also the Science Team Leader for the NASA Earth Observing System (EOS) facility instrument called the Moderate Resolution Imaging Spectroradiometer (MODIS). Prior to being Senior Scientist, he was the Director of the Earth Sciences Directorate at the NASA GSFC from 1990 to 2000. He served at the GSFC as the Deputy Director for Earth Sciences in the Space and Earth Sciences Directorate (1988 to 1990), as Chief of the Laboratory for Terrestrial Physics (1980 to 1988), as Project Scientist for Landsat 4 and 5 (1977 to 1989), as Head of the Hydrospheric Sciences Branch (1973 to 1980), and as a Research Meteorologist (1968 to 1973). Prior to joining the GSFC, he spent three years as Weather Officer in the United States Air Force (1959 to 1962). His publication record shows over 130 publications in scientific journals, conference proceedings, and NASA reports.



Igor Appel received the B.S. degree in oceanography from the Hydrometeorological University, St. Petersburg, Russia, in 1971, the Ph.D. degree in oceanography and the Dr.Sci. degree in oceanography from the Arctic and Antarctic Research Institute, St. Petersburg, in 1978 and 1989, respectively.

He was with the Arctic and Antarctic Research Institute, then he moved to Alaska and Washington. His experience in remote sensing consists of development of new approaches and original algorithms to extract information from Landsat, AVHRR, MODIS,

NPOESS, DMSP satellites, and SAR data. His approach to algorithm development is based on the assumption that the best quality of environmental data records is obtained through study of pixel-by-pixel variation in spectral endmembers and algorithm parameters. Proposed snow and ice VIIRS algorithms synthesize various forms of spectral mixture analysis, surface temperature, and energy balance.